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# Comprehensive review of cooling and heating degree days characteristics over Kingdom of Saudi Arabia

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ABSTRACT

This paper presents the annual and seasonal cooling (CDD) and heating (HDD) degree day values over Saudi Arabia by utilizing the long-term daily average temperatures from 38 meteorological stations. The values of CDDs and HDDs have been calculated for a base temperature of 18.3 °C. The maximum annual mean CDDs of 7549 were observed at Makkah while the minimum of 3132 at Abha. On the other hand the maximum HDDs of 985 were found in Guriat and minimum of 0 at Gizan, Jeddah, Rabigh, Makkah, Sabya, Sharourah, Wejh and Yanbu. The annual and seasonal values of CDD and HDD provided in this paper could be used to estimate the fuel or energy requirement for cooling or heating of buildings in respective areas both on annual and seasonal bases.



**Contents**



## 1. Introduction

Globally increasing demands of energy have become the matter of concern to people from all walks of life due to its adverse effect on the climatic conditions of the earth. The Saudi Arabian population is also increasing at around 2% but the energy demand is going up every year by 4–5%. The erection of fossil fuel based power plants is both time and money intensive. Moreover each MW of electricity produced using mixed fossil fuel adds up around 1.5–1.7 t of green house gases (GHGs) equivalent to $CO_2$ into the atmosphere. Hence means should be explored to protect environment and at the same time meet the energy demands needs of the people. According to energy conservation experts, implementation of incentive oriented policies and awards [1–4], careful design of the building fabric [5] including the size and orientation of windows, thermal insulation [6], solar shading [7], application of ventilated double-skin facade to buildings in hot-summer and cold-winter zone [8,9] and utilization of new and clean sources of energy [10–14] may assist in reducing solar heat gain.

According to Liu et al. [15], human beings have no choice but to reduce energy consumption to combat adverse environmental changes. This can be achieved by increasing the efficiency of energy conservation and exploitation of new and clean sources of energy. Ma and Wang [16] provided an overall review of the building energy research and efforts in Hong Kong over the last decade. Day et al. [17] described how energy/degree-day correlations can be properly identified while taking into consideration

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the energy balance of the building. This methodology further helps in identifying the building base temperature from reduced data sets. Yuan et al. [18] presented a systematical review and prospective analysis on policy evolution and progress of energy conservation and emission reduction in China during the 11th financial year plan. Accordingly China has achieved 3.9% annual energy saving from 1980 to 2005. Caia and Jiang [19] studied the differences in energy consumption between rural and urban households to assess energy conservation implications in five cities. Energies used in urban households are more convenient, cleaner, and more efficient than those used in rural areas, where biomass and coal are common fuels. Furthermore, the energy consumptions in the rural and domestic sectors directly affect the sustainable and balanced economic development [20] and household energy consumption in rural areas also composes an important part of China's national energy consumption [21].

Ambient temperature variations directly affect transportation, water resources, power generation, agriculture, construction, and in particular the energy consumption for cooling and heating of buildings [22,23]. Several case studies have indicated considerable impacts of temperature changes on energy consumption in buildings [24–28]. Degree-day, which is truncation of daily temperature series at a base temperature, is usually accepted as an index of energy consumption for heating and cooling of the buildings [26,27]. As early as 1983, Walsh and Miller [29] presented a simple graphical means for predicting degree day totals for a given period as a function of the mean and standard deviation of the daily average outdoor temperature.

According to Buyukalaca et al. [30], the degree-day method is the simplest method used in Heating, Ventilating and Air-Conditioning industries to estimate heating and cooling energy requirements. The authors estimated HDD and CDD for different base temperatures and presented in the form of tables and the contour maps using temperature data from 78 weather stations in Turkey. Kodah and El-Shaawari [31] recommended a heating base temperature of 15.5 °C for Jordan while Badescu and Zamfir [32] 18 °C for heating degree-day calculations for Romania. Papakostas and Kyriakis [33] reported the heating and cooling degree-hours for two cities of Greece, viz. Athens and Thessaloniki. Recently, Christenson et al. [34] analyzed time series data for the present-day and future climates and estimated heating and cooling degree-days. Their analysis showed that heating degree-days decrease whereas cooling degree-days continue to increase in future climates.

The impact of climate warming on Swiss building energy demand was investigated by means of the degree-day method by Mourshed [35]. During 1901–2003, the HDDs were found to have decreased by 11–18%, depending on the threshold temperature (8, 10 or 12 °C) and location. Jiang et al. [36] reported that heating degree-days varied between 2700 and 7973 °C for a base temperature of 18 °C and heating degree days between 0.4 and 792 °C at a base temperature of 24 °C. Gelegenis [37] reported a simplified second-degree expression for the estimation of annual HDD at various base temperatures. The quadratic relation proved to be quite accurate when applied to data from many cities from Greece and other countries. Papakostas [38] presented annual values of heating and cooling degree-days for typical base temperatures of 15 °C for heating and 24 °C for cooling for Athens and Thessaloniki, Greece. The results showed a reduction of the heating energy demand by 11.5% and 5% and an increase of the cooling energy demand by 26% and 10%, for Athens and Thessaloniki respectively.

Energy conservation is one of the important avenues which could be very effective in meeting the energy demands and at the same time safeguarding our environment and the earth, our home. The present study aims at studying the variation of degree-days and providing the maps of cooling and heating degree-days for the Kingdom so that these could be used effectively in designing and managing the cooling and heating


Fig. 1. Location map of meteorological stations used in the present study.

systems both in residential and industrial (with little modification) applications. The cooling and heating degree day maps can also be used to estimate energy consumption in buildings. Furthermore, such maps may also help in studying the sensitivity of changing the base temperature on energy consumption.

## 2. Study area and methodology

In Saudi Arabia, most of the industrial complexes as well as desalination and power plants are situated in the coastal areas. As a result of this setup, the residential and commercial areas have also developed in and around such zones. For example, Dhahran is situated on the east coast of Saudi Arabia and the main industrial zones as well as desalination and power plants are situated in Dammam, Al-Khobar, Quarraya and Jubail areas. Similarly, the cities of Yanbo, Al-Wejh, Jeddah and Gizan have developed and are in different stages of development. Jubail and Yanbo are the two major industrial zones in the Kingdom. Industrial zones are being developed in Gizan, Rabigh, Al-Jouf, and other areas. The locations of the study zones are shown in Fig. 1. Being a hot and humid country, the energy requirement is rapidly increasing. The study utilizes the daily maximum and minimum values of the temperatures to estimate the different degree-days as mentioned above. The data reporting period spans between 1970 and 2006 i.e. over 37 years. The meteorological data used in this study is collected by the Presidency of Meteorology and Environment (PME) in Saudi Arabia.

Degree-day values are essential data for one who needs to manage the significant energy consumption related to the heating or cooling of buildings. Degree-day value quantifies how cold or hot the weather has been as a single index number for a particular region and a particular period like month or week and can be used, in conjunction with activity-based targeting, to expose abnormal seasonal patterns of consumption, detect exceptional consumption caused by faults, set and track fuel budgets, normalize the performance of different buildings to a common basis for comparison purposes, verify and quantify the savings achieved by energy-saving measures after allowing for weather variations, extrapolate annual consumption from a limited period of monitoring and estimate the peak daily demand. In a nutshell, the degree-day values allow proper accounting for the effect of weather on energy consumption.

The degree-day method for estimating the cooling degree-days is based on the assumption that energy consumption is proportional to the difference between the daily mean temperature and a cooling base temperature of 18.3 °C [39,40]. On the other hand, for estimating the heating energy requirement, it is assumed that the energy consumption is proportional to the temperature difference between daily mean and the heating base of 18.3 °C. Finally, in order to determine the industrial degree-days, base temperatures of 7 °C and 13 °C were used [39–43]. According to the standards (ASHRAE [41]), the difference between the average temperature and the base temperature is called a degree-day.

### 2.1. Estimation of cooling degree-days (CDDs)

The daily cooling degree-days (CDDs) are defined as the difference between the mean temperature and the base cooling temperature of 18.3 °C as given by Eq. (1), and have the same unit as temperature. When the mean temperature is below the base temperature then the cooling degree-day for that day is zero [44].

$$\mathrm{CDD} = T_\mathrm{m} - T_\mathrm{b} \tag{1}$$

where $T_\mathrm{b}$ is the base temperature of 18.3 °C, and $T_\mathrm{m}$ is the daily mean air temperature and is calculated as

$$T_\mathrm{m} = \frac{(T_\mathrm{max} + T_\mathrm{min})}{2} \tag{2}$$

where $T_\mathrm{max}$ and $T_\mathrm{min}$ are the daily maximum and minimum air temperatures. For a certain period of time (weekly, monthly, seasonal, annual, etc.), accumulated cooling degree-days (ACDDs) are calculated using the following expression:

$$ACDD = \sum_{j=1}^{N} (\mathrm{CDD}_j) \quad \begin{cases} \text{if } T_\mathrm{m} > T_\mathrm{b} \text{ then } \mathrm{CDD} = T_\mathrm{m} - T_\mathrm{b} \\ \text{else } \ \mathrm{CDD} = 0 \end{cases} \tag{3}$$

where $N$ is the period of time i.e. number of days in the year, month or week. The corresponding number of days for cooling degree-days was also determined and is discussed in the paper. The corresponding number of days can be used to define the length of the cooling season for a residential and commercial building for any location. The corresponding number of days for the accumulated cooling degree-days for any period of time is determined by summing the days with $T_\mathrm{m}$ greater than $T_\mathrm{b}$.

**Table 1**
Site specific latitude, longitude, and altitude of the stations used in this study and annual cooling degree-days (CDDs) and heating degree-days (HDDs).

| Station | Latitude (°N) | Longitude (°E) | Elevation (m) | CDD | HDD |
|---|---|---|---|---|---|
| Abha | 18.2 | 42.7 | 2084 | **3132** | 486 |
| Afif | 23.9 | 42.9 | 963 | 5722 | 166 |
| Al-Ahsa | 25.3 | 49.5 | 172 | 6054 | 200 |
| Al Hawiyah | 29 | 38.6 | 894 | 4011 | 854 |
| Al Bahah | 20 | 41.5 | 1021 | 5543 | 11 |
| Al-Jawf | 29.8 | 39.9 | 771 | 4128 | 859 |
| Al-Jubail | 27 | 49.7 | 56 | 6266 | 29 |
| Al-Khafji | 28.4 | 48.5 | 80 | 6149 | 137 |
| Al-Kharj | 24.2 | 47.5 | 506 | 6168 | 129 |
| Al Ras | 25.9 | 43.5 | 807 | 5545 | 327 |
| Arar | 30.9 | 41.1 | 552 | 4195 | 963 |
| Az zulfi | 26.3 | 44.8 | 653 | 5560 | 363 |
| Bisha | 20 | 42.6 | 1157 | 5555 | 6 |
| Dariyah | 24.7 | 42.9 | 930 | 5610 | 250 |
| Dhahran | 26.3 | 50.2 | 17 | 5953 | 142 |
| Dowadmi | 24.5 | 44.4 | 840 | 5616 | 265 |
| Gassim | 26.3 | 43.8 | 650 | 5361 | 389 |
| Gizan | 16.9 | 42.6 | 3 | 7347 | 0 |
| Guriat | 31.4 | 37.3 | 499 | 3571 | **985** |
| Hafr Al-Baten | 28.3 | 46.1 | 355 | 5510 | 470 |
| Hail | 27.4 | 41.7 | 1013 | 4428 | 601 |
| Jeddah | 21.7 | 39.2 | 12 | 6587 | 0 |
| Khaamis Mushait | 18.3 | 42.8 | 2054 | 3390 | 393 |
| Madina | 24.6 | 39.7 | 631 | 6680 | 9 |
| Makkah | 21.5 | 39.8 | 310 | **7549** | 0 |
| Nejran | 17.6 | 44.4 | 1203 | 5605 | 12 |
| Rabigh | 22.8 | 39 | 524 | 6207 | 0 |
| Rafha | 29.6 | 43.5 | 447 | 4830 | 676 |
| Riyadh | 24.9 | 46.7 | 612 | 5688 | 291 |
| Sabya | 17.2 | 42.6 | 700 | 5774 | 0 |
| Safwa | 26.7 | 50 | 101 | 6331 | 46 |
| Sharourah | 17.5 | 47.1 | 722 | 6726 | 0 |
| Tabouk | 28.4 | 36.6 | 770 | 4359 | 571 |
| Taif | 21.5 | 40.6 | 1449 | 4528 | 188 |
| Turaif | 31.7 | 38.7 | 813 | 3395 | 1168 |
| Umm Lajj | 25 | 37.3 | 484 | 5836 | 46 |
| Wejh | 26.2 | 36.5 | 16 | 5438 | 0 |
| Yanbu | 24.2 | 38.1 | 1 | 6325 | 0 |

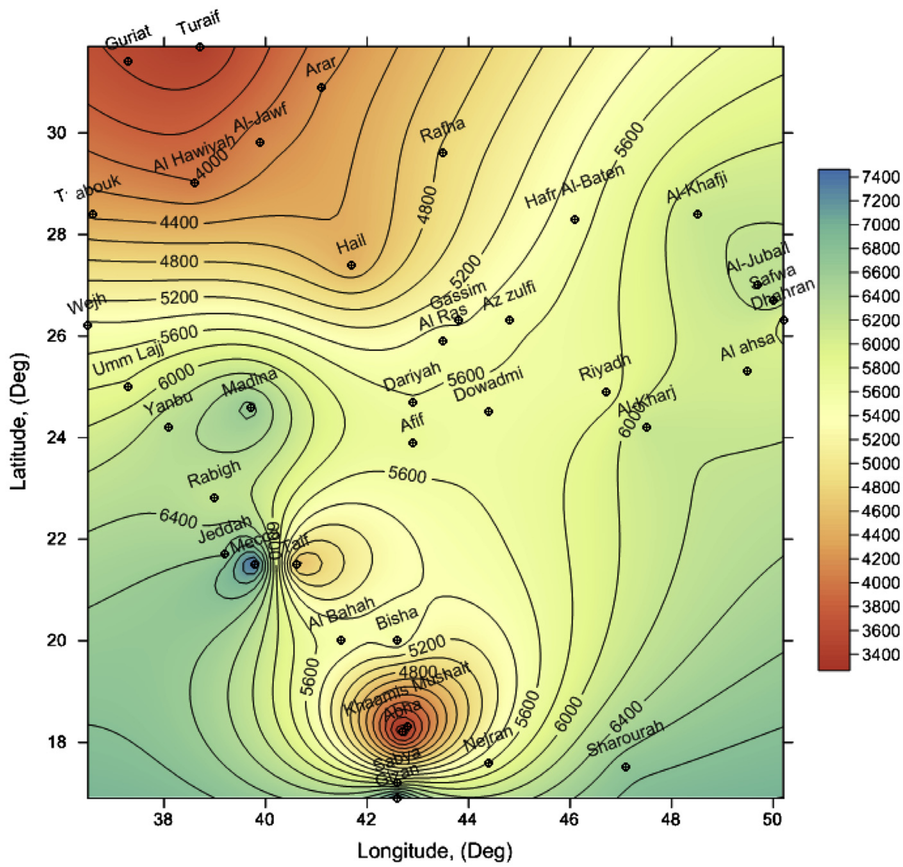


**Fig. 2.** Cooling degree days contour map of Saudi Arabia.

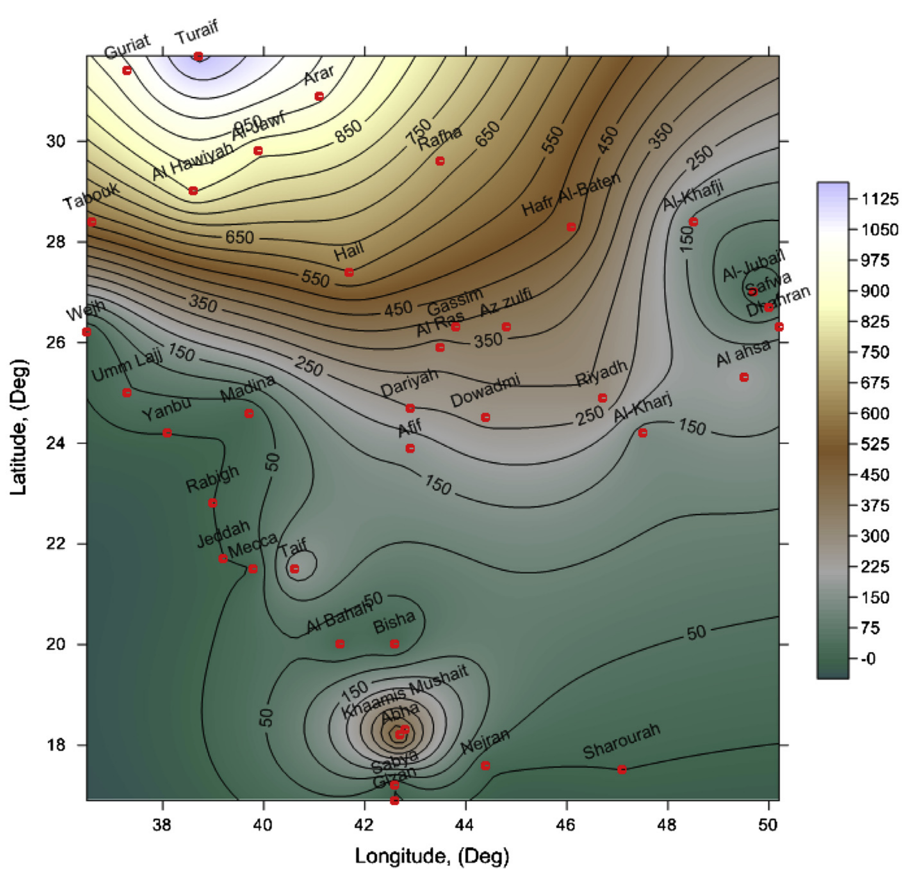


**Fig. 3.** Heating degree days contour map of Saudi Arabia.

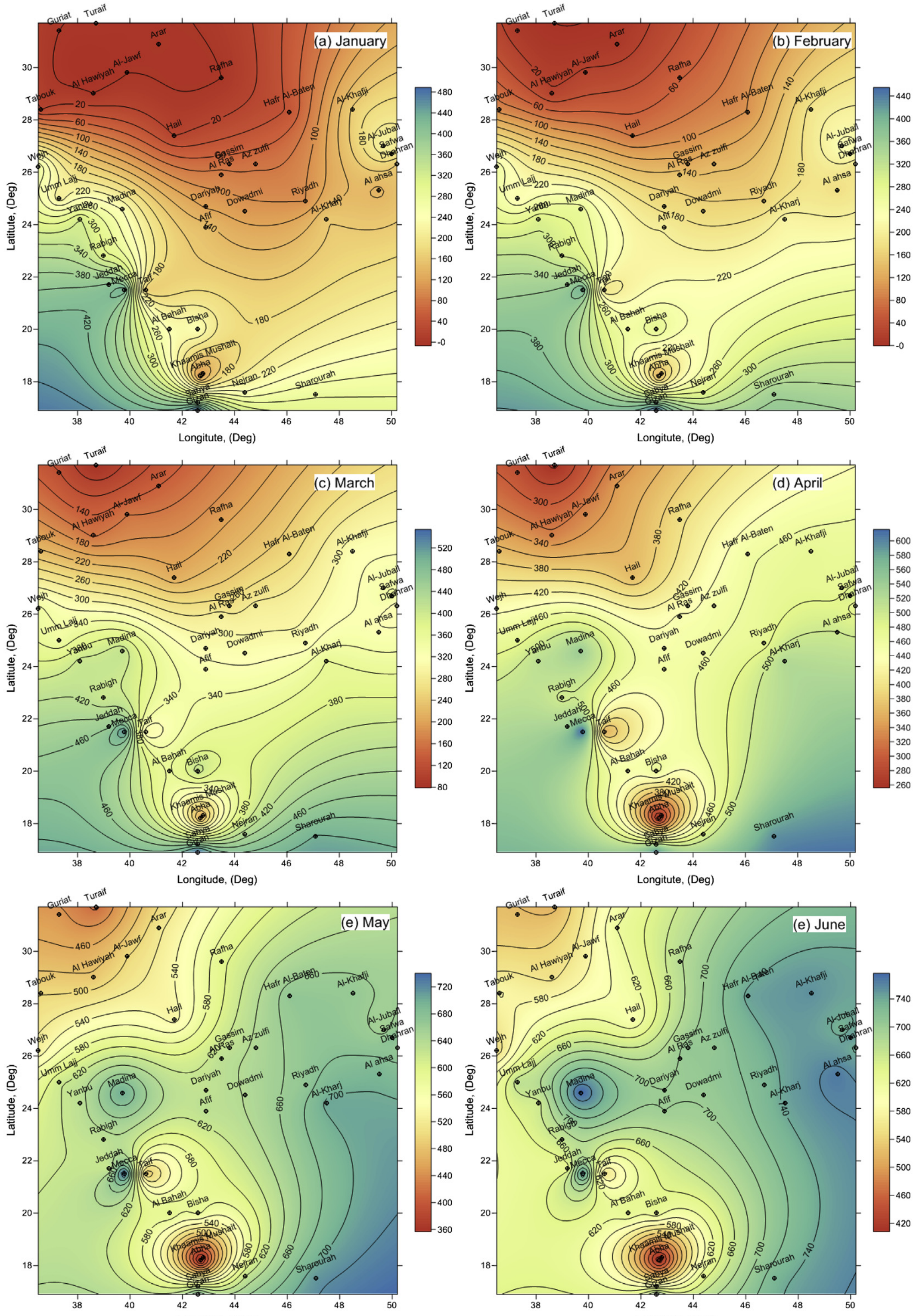


**Fig. 4.** Monthly mean variation of cooling degree-days over Saudi Arabia during January–June.

## 2.2. Estimation of heating degree-days (HDDs)

The daily heating degree-day (HDD) is defined as the deviation of the mean temperature from a heating base temperature of 18.3 °C and is estimated using Eq. (4). When the mean temperature is greater than the base temperature the degree-day for that day is zero [43].

$$HDD = T_b - T_m \tag{4}$$

For a certain period of time (weekly, monthly, seasonal, annual, etc.), accumulated heating degree-days (AHDDs) are calculated using

the following expression:

$$AHDD = \sum_{j=1}^{N} (HDD_j) \quad \begin{cases} \text{if } T_m < T_b \text{ then } HDD = T_b - T_m \\ \text{else } HDD = 0 \end{cases} \tag{5}$$

where $N$ is defined as the period of time (number of days). The corresponding numbers of days for heating degree-days were also determined. The corresponding number of days can be used to estimate the length of the heating season for a residential and commercial building. The corresponding number of days for the accumulated heating degree-days for any period of time is determined by summing the days with $T_m$ less than $T_b$.

## 3. Results

This section is devoted to discussion of the results obtained using methodology presented in the previous section. The long-term values of CDDs and HDDs for all the meteorological stations,

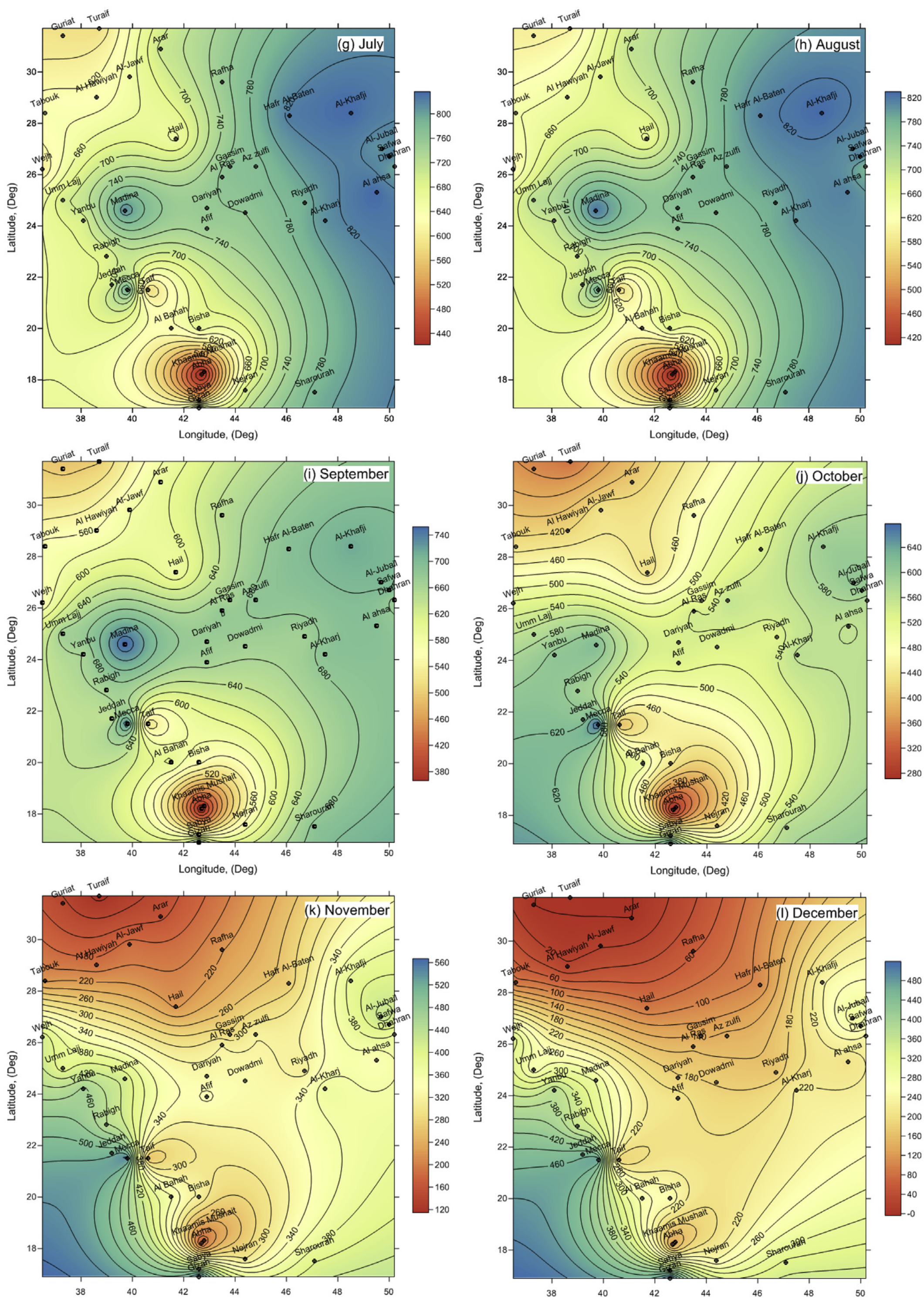


**Fig. 5.** Monthly mean variation of cooling degree-days over Saudi Arabia during July–December.

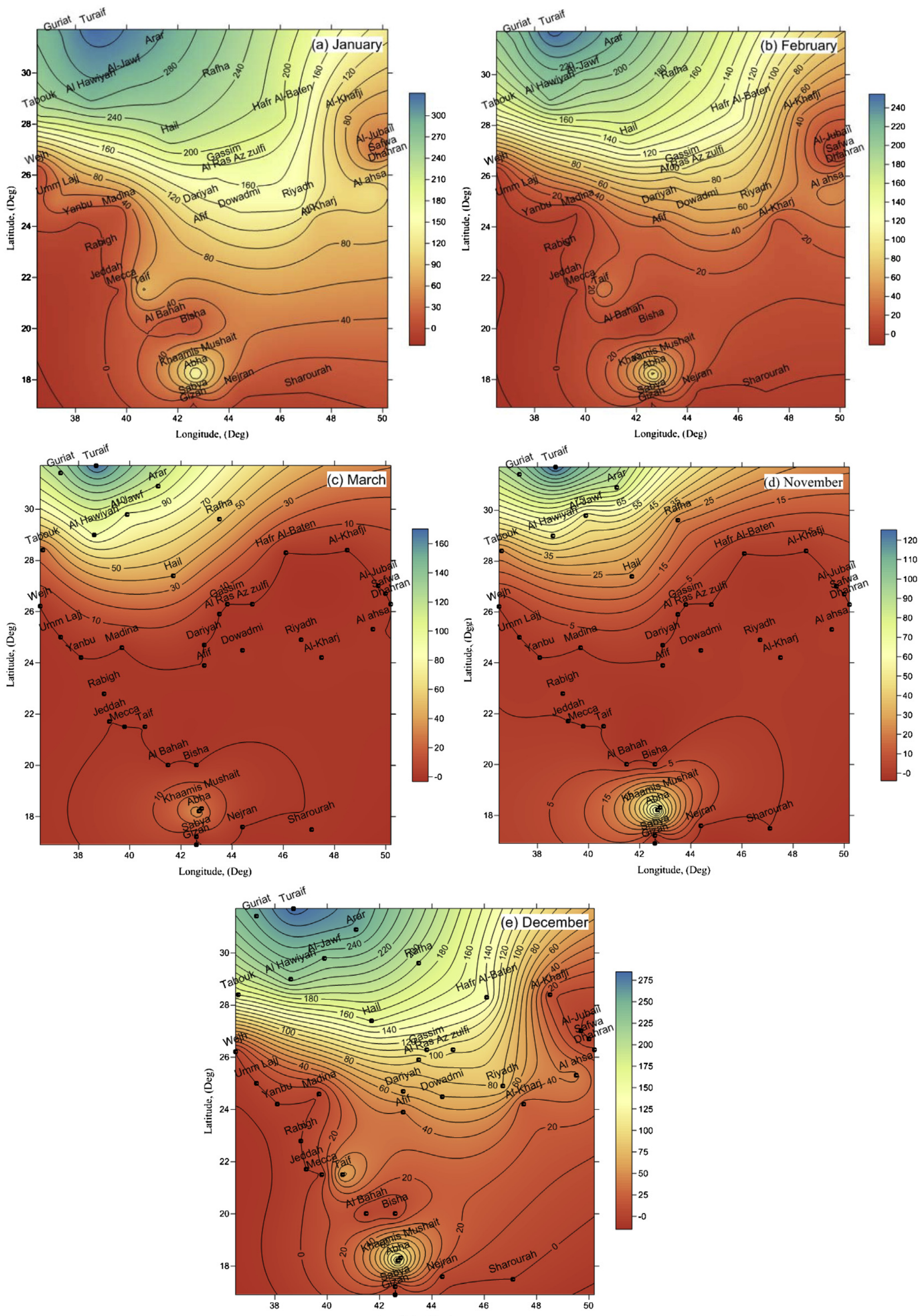


**Fig. 6.** Monthly mean variation of heating degree-days over Saudi Arabia during January–March and November–December.

representing inhabitant regions, are summarized in Table 1. The variation of CDDs over Saudi Arabia is shown in the contour map of Fig. 2. The heating degree days distribution over Saudi Arabia is shown in Fig. 3.

The monthly mean values of CDDs and HDDs were obtained for all the locations and contour maps were prepared to study the effect of seasons on the behavior and magnitude of the two. The maps of CDDs for all the months from January to December are shown in Figs. 4 and 5 while those for HDDs are depicted in Fig. 6.

The monthly variations of CDDs (Fig. 7) in relation to corresponding values of dew point temperature (Fig. 8) and vapor pressure (Fig. 9) for some major cities of the Kingdom are discussed here to have further better understanding of these parameters.

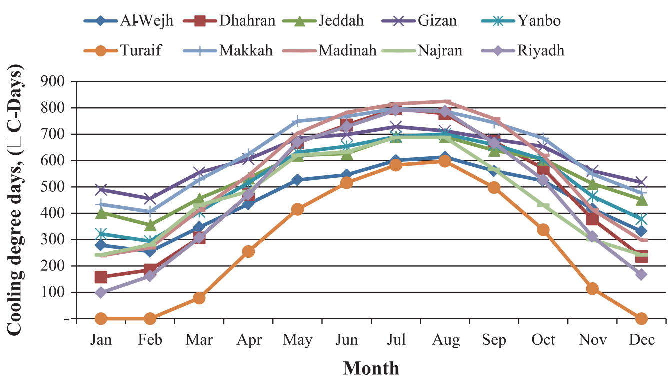


**Fig. 7.** Long-term monthly mean values of CDD for some selected areas.

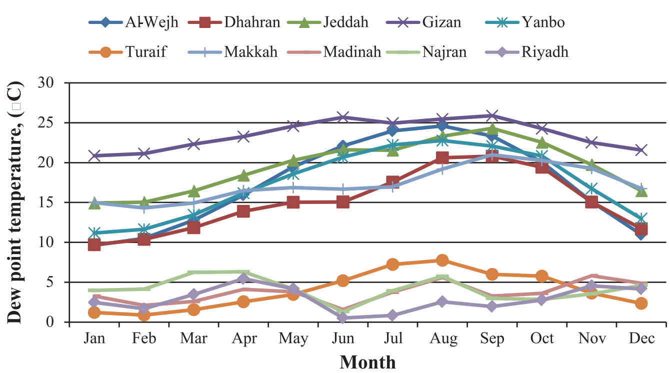


**Fig. 8.** Long-term monthly mean values of dew point temperature for some selected areas.

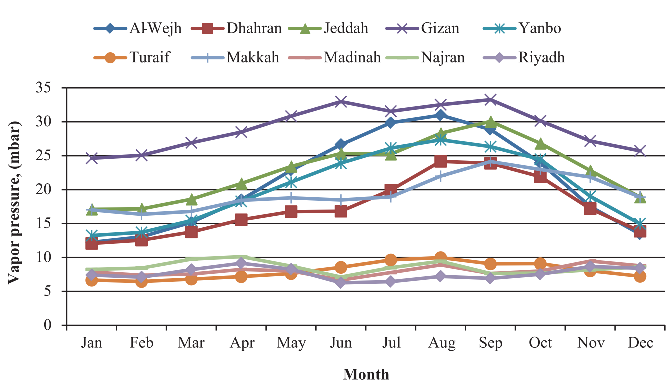


**Fig. 9.** Long-term monthly mean values of vapor pressure for some selected areas.

## 4. Discussion

The CDD values varied between a minimum of 3132 °C-days and a maximum of 7549 °C-days corresponding to Abha and Mecca, respectively. At Gizan also a very high number of CDD's of 7347 °C-days was obtained. At Al-Ahsa, Al-Jubail, Al-Khafji, Al-Kharj, Jeddah, Madina, Rabigh, Safwa, and Yanbu more than 6000 °C-days (CDD) were observed. In **A**bha and Turaif regions, the CDD values were less than 4000 (Fig. 2). Higher values of HDD of more than 950 °C-days were observed at Arar, Turaif and Abha regions. In general, higher HDDs were observed in the northern region and lower in the central and the southern regions, with the exception of hilly areas like Taif, Khamis-Mushait and Abha, where some heating was required, as can be seen from the contour map of Fig. 3. Lower values of ( $<250$ °C-days) HDDs were found in the regions starting from Al-Khafji and marching toward Riyadh, Al-Kharj, Dowadmi, Dariyah, Afif, etc., as shown in Fig. 3. Almost no heating was required at Wejh, Umm Lajj, Yanbu, Rabigh, Madina, Jeddah, Mecca, Al-Baha, Bisha, Al-Jubail, Dhahran, and Safwa, as indicated in Fig. 3.

Heating was required only from January to March and then from November to December and that too at a few locations only. The CDD map during January showed almost zero values in the northernmost part of the Kingdom which gradually picked up on moving toward south and maximum concentration could be seen in the south western region (Fig. 4(a)). The central zone from Wejh to Dhahran through Dariyah, Az Zilfi, Dowadmi, and Riyadh showed mild values of CDDs as can be seen from Fig. 4(a) for January. In February (Fig. 4(b)), the situation changed a bit and the northern area with almost zero CDDs moved a bit up, which means the region with smaller values of CDDs shrank compared to that in January and the southern region expanded with higher values of CDD's. This pattern was observed to be transforming from lower to higher values of CDDs till June (Fig. 4(f)). The maximum concentration of CDDs was observed in Madina, Makkah, Gizan and south eastern part of Saudi Arabia.

Furthermore, the seasonal transformation of low or almost no CDDs was observed toward end of the year i.e. in December (Fig. 5 (f)). Between July and December, the trends of changing values of CDDs could be clearly noticed. In Saudi Arabia, heating is rare and is required in very few places as observed from seasonal maps of HDDs shown in Fig. 6. In January the maximum HDDs were observed in Guriat, Turaif and the adjoining region while moderate heating was seen in the central part and a minimal in the southern region (Fig. 6(a)). In February, the regions requiring heating reduced or shrank toward north and lower heating areas expanded as compared to those in January. In March, as seen from Fig. 6(c), the heating region was found to be limited only around Turaif and almost no heating was observed in rest of the region. Toward the end of the year, again the heating requirement increased as could be seen from Fig. 6(e).

It is evident from Fig. 7 that the CDDs have a clear seasonal pattern with lower values in winter time and higher during summer time with higher seasonal range in the northern region and lower range in central and southern areas. Moving from Turaif in the north toward Najran in the south through Madina in the west central and Riyadh in the central region, an increasing trend toward the central region and then again a decreasing pattern toward south were noticed. Both of these stations (Medina and Riyadh) are inland stations and are 646 and 624 m above mean sea level respectively. At Turaif the maximum CDD value was 598 °C-days in August while at Madina and Riyadh these values were 825 and 791 °C-days corresponding to August and July months, respectively. Finally, at Najran the CDD value decreased to 688 °C-days in July and August. The dew point temperature at Turaif (Fig. 8) followed almost the same trend with greater range while vapor pressure was almost the same during the entire year (see Fig. 9). Turaif is an inland station and is a few hundred kilometers away from both the Red Sea and Arabian Gulf Sea. At all these four stations, the dew point temperature varied from 0 to 8 °C while the vapor pressure changed from 5 to 10 mbar.

At coastal locations (Al-Wejh, Yanbo, Jeddah, Dhahran, and Gizan), which are the centers of human and economic activities and developments, the highest values of CDDs were observed in July and August and the lowest in January and December, as can be seen from Fig. 7. The values of dew point temperature were also found to be following almost the same trend (Fig. 8).

Except at Al-Wejh (near Red Sea shoreline and about 2 m above mean sea level), the maximum values of dew point occurred in the month of September, where it was found in July. All time

maximum dew point and vapor pressure were found at Gizan as can be observed from Figs. 8 and 9, respectively. This station is located very close to the sea i.e. only 50 m away from waterline and about 4 m above mean sea level. Furthermore, the trends and magnitudes of the monthly mean values of CDDs were found to be in close agreement with the trend and magnitude of dew point temperatures and the vapor pressure at all the representative sites. The cooling and heating requirements of buildings are not linearly dependent on ambient temperature but also on other several factors which should be taken into account while estimating energy requirement of a building. These factors may include level of insulation in the building, electrical appliances being used, outside wind speed, and the relative humidity.

## 5. Conclusions and recommendations

High values of more than 7000 °C-days of CDDs were observed at Gizan and Mecca. At Al-Ahsa, Al-Jubail, Al-Khafji, Al-Kharj, Jeddah, Madina, Rabigh, Safwa, and Yanbu more than 6000 °C-days (CDD) were observed. Between 5000 and 6000 °C-days (CDDs) were observed at Afif, Al Bahah, Al Ras, Az zulfi, Bisha, Dariyah, Dhahran, Dowadmi, Gassim, Hafr Al-Baten, Nejran, Riyadh, Sabya, Umm Lajj, and Wejh areas. The least values of 3500 and less of CDDs were observed in Turaif and Guriat in the northernmost and Khamis-Mushait and Abha in the south of the country. Khamis-Mushait and Abha are hill stations and are situated at 2060 and 2084 m above mean sea level, respectively, and because of this reason have less number of CDDs. In general, higher values of CDDs were observed at coastal locations and plain areas irrespective of surface elevation with the exception of hill stations.

Overall, little heating was required over the entire nation with the exception of around 1000 °C-days (HDDs) in Turaif, Guriat and Baha areas. Lower values of HDD's ( $<250$ °C-days) were found in Al-Khafji, Riyadh, Al-Kharj, Dowadmi, Dariyah, and Afif areas while almost no heating was required at Wejh, Umm Lajj, Yanbu, Rabigh, Madina, Jeddah, Mecca, Al-Baha, Bisha, Al-Jubail, Dhahran, and Safwa. Evident patterns of changing number of cooling and heating degree-days were noticed in different months of the year. These seasonal maps of CDD and HDD will be of importance to design offices involved with local building designs. Finally, the trends and magnitudes of the monthly mean values of CDDs were found to be in close agreement with the trend and magnitude of dew point temperatures and the vapor pressure at all the representative sites.

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